

Measurement of the CP Asymmetry and Branching Fraction of $B^0 \rightarrow \rho^0 K^0$

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We present a measurement of the branching fraction and time-dependent CP asymmetry of $B^0 \rightarrow \rho^0 K^0$. The results are obtained from a data sample of $227 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the BABAR detector at the PEP-II asymmetric-energy B Factory at SLAC. From a time-dependent maximum likelihood fit yielding 111 ± 19 signal events we find $\mathcal{B}(B^0 \rightarrow \rho^0 K^0) = (4.9 \pm 0.8 \pm 0.9) \times 10^{-6}$, where the first error is statistical and the second systematic. We report the measurement of the CP parameters $S_{\rho^0 K_S^0} = 0.20 \pm 0.52 \pm 0.24$ and $C_{\rho^0 K_S^0} = 0.64 \pm 0.41 \pm 0.20$.

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Decays of B^0 mesons to the $\rho^0 K^0$ final state are expected to be dominated by $b \rightarrow s$ penguin amplitudes. Neglecting Cabibbo-Kobayashi-Maskawa (CKM) suppressed amplitudes, the mixing-induced CP violation parameter $S_{\rho^0 K_S^0}$ should equal $\sin 2\beta$, which is well measured in $B^0 \rightarrow J/\psi K^0$ decays [1]. Within the Standard Model (SM), only small deviations from this prediction are expected [2]. In the Standard Model, a single phase in the CKM matrix governs CP violation [3], but if heavy non-SM particles appear in additional penguin diagrams, new CP -violating phases could enter and $S_{\rho^0 K_S^0}$ would not equal $\sin 2\beta$ [4]. Observation of a significant discrepancy would be a clear signal of new physics.

In this Letter we present the first observation of the decay $B^0 \rightarrow \rho^0 K^0$ and a measurement of the CP -violating asymmetries $S_{\rho^0 K_S^0}$ and $C_{\rho^0 K_S^0}$ from a time-dependent maximum likelihood analysis. A non-zero value of $S_{\rho^0 K_S^0}$ indicates CP violation due to the interference between decays with and without mixing. Direct CP violation leads to a non-zero value of $C_{\rho^0 K_S^0}$. We take a quasi-two-body (Q2B) approach, restricting ourselves to the region of the $B^0 \rightarrow \pi^+\pi^- K_S^0$ Dalitz plot dominated by the ρ^0 and treating other $B^0 \rightarrow \pi^+\pi^- K_S^0$ contributions as non-interfering background. The effects of interference with other resonances are estimated and taken as systematic uncertainties.

The data were collected with the BABAR detector at the PEP-II asymmetric-energy e^+e^- storage ring at SLAC. An integrated luminosity of 205 fb^{-1} , corresponding to $227 \times 10^6 B\bar{B}$ pairs, was collected at the $\Upsilon(4S)$ resonance (center-of-mass (CM) energy $\sqrt{s} = 10.56 \text{ GeV}$), and 16 fb^{-1} was collected about 40 MeV below the resonance (off-resonance data). The BABAR detector is described in detail elsewhere [5]. Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), consisting of five layers of double sided detectors, and a 40-layer central drift chamber (DCH), both operating in the 1.5 T magnetic field of a solenoid. Charged-particle identification is provided by the average energy loss in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region.

We reconstruct $B^0 \rightarrow \rho^0 K_S^0$ candidates (B_{rec}^0 in the following) from combinations of ρ^0 and K_S^0 candidates, both reconstructed in their $\pi^+\pi^-$ decay mode. For the $\pi^+\pi^-$ pair from the ρ^0 candidate, we remove tracks identified as very likely to be electrons, kaons, or protons.

The mass of the ρ^0 candidate is restricted to the interval $0.4 < m(\pi^+\pi^-) < 0.9 \text{ GeV}/c^2$. The K_S^0 candidate is required to have a mass within $13 \text{ MeV}/c^2$ of the nominal K_S^0 mass [6] and a decay vertex separated from the ρ^0 decay vertex by at least three times the estimated separation measurement uncertainty. In addition, the cosine of the angle in the lab frame between the K_S^0 flight direction and the vector between the ρ^0 decay vertex and the K_S^0 decay vertex must be greater than 0.995. Vetoes against $B^0 \rightarrow D^+\pi^-$ and $B^0 \rightarrow K^*\pi^-$ ($K^* \rightarrow K_S^0\pi^+$) are imposed by requiring that the invariant masses of both $K_S^0\pi$ combinations are more than $0.055 \text{ GeV}/c^2$ and $0.040 \text{ GeV}/c^2$ from the K^{*+} and D^+ masses [6] respectively. To exclude events with poorly reconstructed vertices we require the estimated error on Δt to be less than 2.5 ps and that $|\Delta t|$ must be less than 20 ps, where Δt is the proper time difference between the decay of the reconstructed B meson (B_{rec}^0) and its unreconstructed partner (B_{tag}^0), $t_{\text{rec}} - t_{\text{tag}}$. It is determined from the measured relative displacement of the two B -decay vertices and the known boost of the e^+e^- system.

Two kinematic variables are used to discriminate between signal and combinatorial background. The first is ΔE , the difference between the measured CM energy of the B candidate and $\sqrt{s}/2$, where \sqrt{s} is the CM beam energy. The second is the beam-energy substituted mass $m_{\text{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where the B_{rec}^0 momentum \mathbf{p}_B and the four-momentum of the initial $\Upsilon(4S)$ state (E_i, \mathbf{p}_i) are defined in the laboratory frame. We require $|\Delta E| < 0.15 \text{ GeV}$ and $5.23 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$.

Continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events are the dominant background. To enhance discrimination between signal and continuum, we use a neural network (NN) to combine five variables: the cosine of the angle between the B_{rec}^0 direction and the beam axis in the CM, the cosine of the angle between the thrust axis of the B_{rec}^0 candidate and the beam axis, the sum of momenta transverse to the direction of flight of the B_{rec}^0 , and the zeroth and second angular moments $L_{0,2}$ of the energy flow about the B_{rec}^0 thrust axis. The moments are defined by $L_j = \sum_i \mathbf{p}_i \times |\cos \theta_i|^j$, where \mathbf{p}_i is its momentum and θ_i is the angle with respect to the B_{rec}^0 thrust axis of the track or neutral cluster i excluding the tracks that make up the B_{rec}^0 candidate. The NN is trained with off-resonance data and Monte Carlo (MC)[7] simulated signal events.

selected signal events are reconstructed incorrectly

with low momentum tracks from the other B meson being used to form the ρ^0 candidate. In total, 20,073 events pass all selection criteria in the on-resonance sample.

An unbinned extended maximum likelihood fit is used to extract the $\rho^0 K_s^0$ CP asymmetry and branching fraction. There are ten components in the fit: signal, continuum background and eight separate backgrounds from B decays. Large samples of MC-simulated events are used to identify these specific B backgrounds. Where an individual decay mode makes a significant contribution to the dataset (one or more events expected in the data) we include it as a separate contribution to the fit. Probability density functions (PDFs) are taken from simulation with the expected number of B background events fixed to values estimated from known branching fractions [6] and MC efficiencies (Table I). Where only upper limits are available, decay modes are not included in the default fit but are used in alternate fits to evaluate systematics.

Events from B decays that do not come from individually significant channels are collected together into two “bulk” B contributions to the fit (B^0 and B^+). The assumption is made that $B^0 \rightarrow f_0(600)K_s^0$ can be neglected, with support from [8, 9] which do not require this mode to describe $B^+ \rightarrow K^+\pi^+\pi^-$.

The events in the data sample have their unreconstructed B s flavor-tagged as B^0 or \bar{B}^0 with the method described in [10]. Events are separated into four flavor-tagging categories and an “untagged” category, depending upon the method used to determine the flavor. Each category has a different expected purity and accuracy of tagging. The likelihood function for the N_k candidates in flavor tagging category k is

$$\mathcal{L}_k = e^{-N'_k} \prod_{i=1}^{N_k} \left\{ N_S \epsilon_k \left[(1 - f_{\text{MR}}^k) \mathcal{P}_{i,k}^{\text{SCR}} + f_{\text{MR}}^k \mathcal{P}_{i,k}^{\text{SMR}} \right] + N_{\text{C},k} \mathcal{P}_{i,k}^{\text{C}} + \sum_{j=1}^{N_B} N_{\text{B},j} \epsilon_{j,k} \mathcal{P}_{ij,k}^{\text{B}} \right\}, \quad (1)$$

where N'_k is the sum of the signal and background yields for events tagged in category k , N_S is the number of $\rho^0 K_s^0$ signal events in the sample, ϵ_k is the fraction of signal events tagged in category k , f_{MR}^k is the fraction of mis-reconstructed (MR) signal events in tagging category k and the superscript CR implies correctly reconstructed signal. $N_{\text{C},k}$ is the number of continuum background events that are tagged in category k , and $N_{\text{B},j} \epsilon_{j,k}$ is the number of B -background events of class j that are tagged in category k . The B -background event yields are fixed in the default fit to values shown in Table I. The values ϵ_k and f^k are determined from MC for B -backgrounds and from a sample of B decays of known flavor for signal. The total likelihood \mathcal{L} is the product of the likelihoods for each tagging category.

Each signal and background PDF is defined as: $\mathcal{P}_k = \mathcal{P}(m_{\text{ES}}) \cdot \mathcal{P}(\Delta E) \cdot \mathcal{P}_k(\text{NN}) \cdot \mathcal{P}(\cos \theta_{\pi^+}) \cdot \mathcal{P}(\Delta t) \cdot \mathcal{P}(m_{\pi^+\pi^-})$

Background Mode	N_{expected}
Bulk B^+	197±98
Bulk B^0	197±98
$B^0 \rightarrow D^+\pi^-$	40±6
$B^0 \rightarrow \eta' K_s^0$	34±5
$B^0 \rightarrow f_0(980)K_s^0$	22±4
$B^0 \rightarrow K_0^*(1430)^+\pi^-$	7±1
$B^0 \rightarrow \rho^0 K^{*0}$	3±3
$B^0 \rightarrow (K_s^0 \pi^+ \pi^-)_{\text{NR}}$	2±1

TABLE I: Expected number of events from each B background source.

where m_{ES} , ΔE , NN, $m(\pi^+\pi^-)$ are the variables described previously, and $\cos \theta_{\pi^+}$ is the angle between the K_s^0 and the π^+ from the ρ^0 in the ρ^0 meson’s center-of-mass frame.

The Δt PDF for signal events is defined as

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \times \left[1 + \frac{\Delta D}{2} + q \langle D \rangle \left(S_{\rho^0 K_s^0} \sin(\Delta m_d \Delta t) - C_{\rho^0 K_s^0} \cos(\Delta m_d \Delta t) \right) \right] \otimes R_{\text{sig}}(\Delta t, \sigma_{\Delta t}), \quad (2)$$

where τ_B and Δm_d are the average lifetime and eigenstate mass difference of the neutral B meson, $q = +1$ (-1) when $B_{\text{rec}}^0 = B^0$ (\bar{B}^0), $\langle D \rangle$ describes the dilution effect from imperfect flavor tagging, and ΔD is the difference in this dilution between B^0 and \bar{B}^0 tags. This formalism is found to effectively describe both correctly and incorrectly reconstructed signal. $\langle D \rangle$, ΔD and the Δt resolution function, $R_{\text{sig}}(\Delta t, \sigma_{\Delta t})$, have parameters fixed to values taken from a sample where B s of known flavor can be reconstructed [10]. “Untagged” events have a $\langle D \rangle$ of 0, reflecting the lack of tag information.

The m_{ES} , ΔE , NN, $\cos \theta_{\pi^+}$ and $m(\pi^+\pi^-)$ PDFs for signal and B background are taken from MC simulation. In general they are non-parametric, with the exception of m_{ES} and ΔE for signal signal PDFs appear as solid curves in Figure 1 The CP parameters for $\eta' K_s^0$ and $f_0 K_s^0$ backgrounds are fixed to $C = 0$ and $S = \sin 2\beta$ (for $\eta' K_s^0$) and $S = -\sin 2\beta$ (for $f_0 K_s^0$), in accordance with SM expectations. For the remaining B backgrounds the parameters C and S are fixed to 0. The PDF parameters describing the continuum background are either allowed to vary freely in the fit or else determined separately from off-resonance data.

There are 16 free parameters in the fit: the yield of signal events, $S_{\rho K_s^0}$ and $C_{\rho K_s^0}$ and 13 that parameterize the continuum background. The continuum parameters are: the yields (5), and those associated with the second order polynomial describing the ΔE distribution (2), the ARGUS [11] function describing the m_{ES} distribution (1) and the double Gaussian used to model the Δt distribution (5).

The fit yields 111 ± 19 signal events. We calculate

the branching fraction from the measured signal yield, efficiency (including the $\rho^0 \rightarrow \pi^+\pi^-$, $K^0 \rightarrow K_S^0$ and $K_S^0 \rightarrow \pi^+\pi^-$ branching fractions), and the number of $B\bar{B}$ events. The result is $\mathcal{B}(B^0 \rightarrow \rho^0 K^0) = (4.9 \pm 0.8 \pm 0.9) \times 10^{-6}$, where the first error is statistical and the second systematic. The likelihood ratio between the fit result of 111 signal events and the null hypothesis of zero signal shows that this is excluded at the 8.7σ level. When additive systematic effects are included we exclude the null hypothesis at the 5.0σ level. The fit for CP parameters gives $S_{\rho^0 K_S^0} = 0.20 \pm 0.52 \pm 0.24$ and $C_{\rho^0 K_S^0} = 0.64 \pm 0.41 \pm 0.20$.

Figure 1 shows $sPlots$ [12] of the discriminating variables in the fit. Knowledge of the level of background and our ability to distinguish it from signal can be gained from the errors in these plots. In addition, Fig. 1(f) shows the ratio $\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_B)$ for all events, where \mathcal{L}_S and \mathcal{L}_B are the likelihoods for each event to be signal or background, respectively.

Figure 2 shows $sPlots$ of Δt . Untagged events are removed, and events are split into B_{tag}^0 tags and \bar{B}_{tag}^0 tags. An $sPlot$ of asymmetry $(N_{B_{\text{tag}}^0} - N_{\bar{B}_{\text{tag}}^0})/(N_{B_{\text{tag}}^0} + N_{\bar{B}_{\text{tag}}^0})$ as a function of Δt is also shown.

Systematic errors are listed in Table II. We estimate biases due to the fit procedure from fits to a large number of simulated experiments. We vary parameters fixed in the nominal fit by their uncertainty and include the change in result as the corresponding systematic error. The systematic uncertainties arise from sources including the parameterization of the signal Δt resolution function, the mistag fractions, and discrepancies between data and the simulation including the effect of alternative models for resonances.

We estimate the systematic uncertainty due to neglecting the interference between $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ from both parameterized and full simulations that take interference into account. We include contributions from $\rho^0(770)K_S^0$, $f_0(980)K_S^0$, $K_0^*(1430)^+\pi^-$, $K_0^*(892)^+\pi^-$ and $f_2(1270)K_S^0$, as well as two $K_S^0 \pi \pi$ non-resonant contributions. We simulate many samples with different relative phases between modes. We also vary the amplitude of each mode within limits based on the best available information [8, 9]. Each simulation is then subjected to the standard selection and fitting procedure. The systematic uncertainty is taken from the width of a Gaussian fitted to the distribution of the results.

In summary, we have established the existence of the decay $B^0 \rightarrow \rho^0 K^0$ and measured its branching fraction with the significance of 5 standard deviations. Our measurement agrees within errors with $\mathcal{B}(B^0 \rightarrow \omega K^0)$ as measured in [13], as expected if a single penguin amplitude dominates these decays. We have extracted the CP violating parameters S and C for $B^0 \rightarrow \rho^0 K_S^0$ which are consistent with those measured in charmonium channels [1].

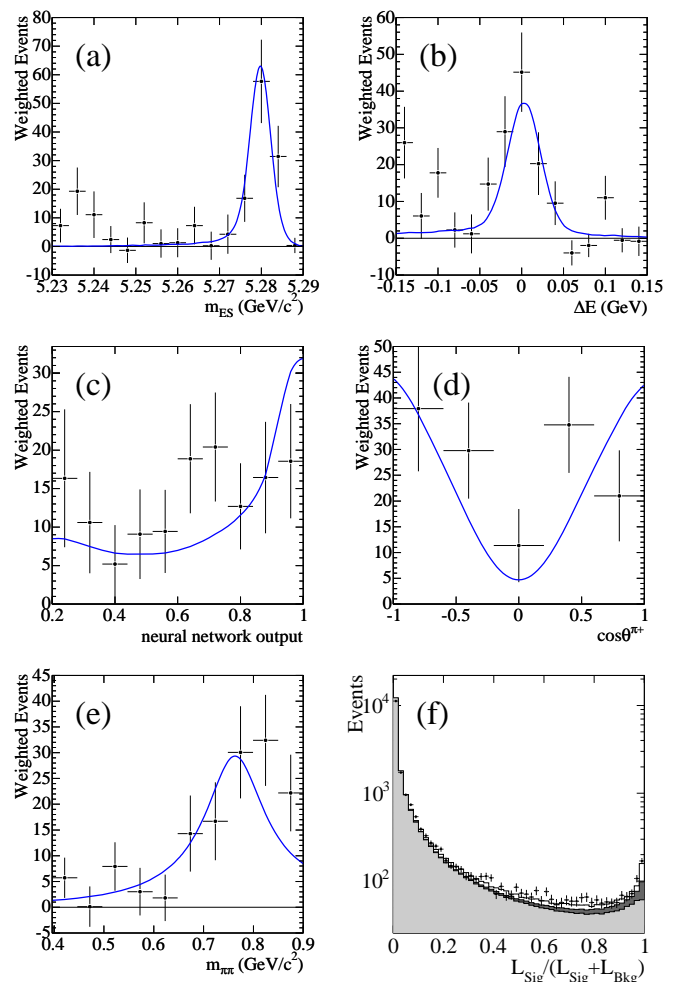


FIG. 1: $sPlots$ of Maximum Likelihood fit discriminating variables: (a) m_{ES} , (b) ΔE , (c) Neural Network output, (d) $\cos \theta_{\pi^+}$, (e) invariant mass of the $\pi^+ \pi^-$ combination. Lines are projections of signal PDFs for each variable. (f) is a plot of the likelihood of an event being signal calculated for all events in our dataset and compared to the predictions of our PDF (predicted continuum in light grey, B Background in dark grey and signal in white).

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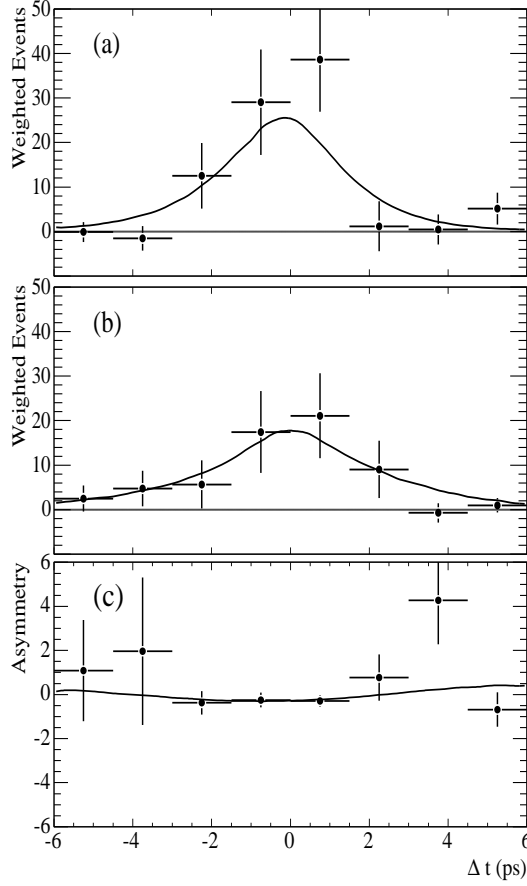


FIG. 2: s Plots of Δt , overlaid with projected signal PDFs, split into (a) B_{tag}^0 tags, (b) \bar{B}_{tag}^0 tags and (c) the asymmetry $(N_{B_{\text{tag}}^0} - N_{\bar{B}_{\text{tag}}^0}) / (N_{B_{\text{tag}}^0} + N_{\bar{B}_{\text{tag}}^0})$ as a function of Δt .

Mis-reco'd events and fit bias	0.12	0.09	10
PDF uncertainties	0.13	0.18	2
Tagging parameters	0.02	0.01	-
Neglect of interference	0.14	0.09	7
ρ^0 mass shape	0.07	0.05	3
B Background BF	0.02	0.10	13
CP of background	0.04	0.00	-
Tracking efficiency & B counting	-	-	6
Total	0.24	0.20	19

TABLE II: Summary of contributions to the systematic error.

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